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Initial Rotor Position Estimation for Sensorless Brushless DC Drives

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Abstract —This paper presents a method to determine the initial rotor position of a brushless DC machine at standstill without a position sensor. The key principle of the rotor position estimation is based on the simple detection and comparison of phase voltage and current responses relating to the stator inductance varied with the position of the rotor magnet. In the proposed method, only three pulse voltage injections are applied and 30 degree resolution can be achieved. Moreover, no knowledge of machine parameters is required. The effectiveness of the proposed method is validated by experimental results.

I. Introduction

Brushless DC (BLDC) motors are widely used in a number of industrial applications such as compressors, electrical vehicles, and hard disk drives because of their high power density, durability, high efficiency, silent operation, and high starting torque, thus making their drives a much more attractive solution in recent years.

Traditionally, a BLDC drive, as shown in Fig. 1, needs a rotor position sensor to ensure stable operation by synchronizing the phase excitation to the rotor position. If the initial rotor position is inaccurately estimated, the starting torque of the motor decreases. Also, the motor may temporarily rotate in reverse direction or may cause starting failure. For these reasons, several papers have been investigated into several methods to eliminate position sensors by using signal injection [1]-[5].

However, most of the previous methods require either sophisticated sensing techniques or time-consuming computational algorithms for the initial rotor position estimation, thus making them impractical for implementation in a low-cost microcontroller.

In this paper, the rotor position estimation is based on a simple detection and comparison technique of phase voltage and current responses, resulting from an applied sequence of only three voltage pulse injections.

The next section of this paper describes the proposed initial rotor position estimation method. Section III presents experimental results to validate and to demonstrate the effectiveness of the proposed method, followed by the conclusion in Section IV.

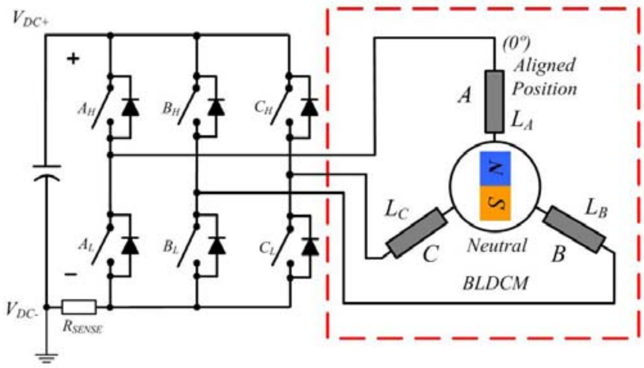


Fig. 1 Inverter-driven three-phase BLDC motor.

II. Proposed Initial Rotor Position Estimation Method

The basic principle of estimating rotor position is based on saturation effect of the stator core, caused by the rotor magnet [1]. Fig. 2 shows measured current response and calculated inductance against the actual rotor position. The response was obtained from measurement of a surface-mounted BLDC machine by injecting a series of voltage pulses into the machine (switching on A_H, B_L and C_L, referred to Fig. 1) at various actual rotor positions. Machine parameters are listed in Table 1.

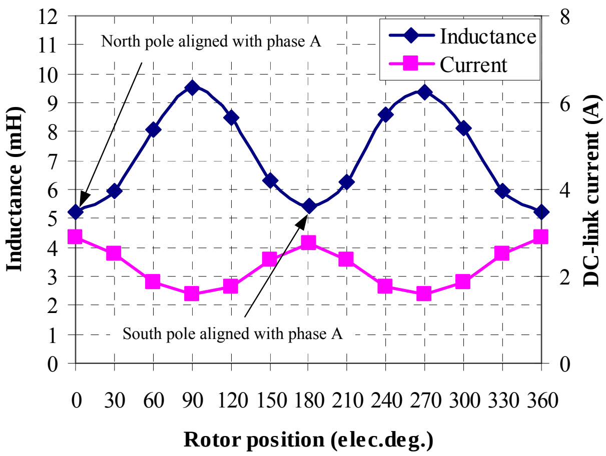


Fig. 2 Measured current response and calculated equivalent inductance versus the actual rotor position of a surface-mounted BLDC machine.

The key principle of the proposed method for detecting the rotor position at standstill is to measure and then compare the stator inductance of each phase.

Table 1 Parameters of the tested BLDC machine

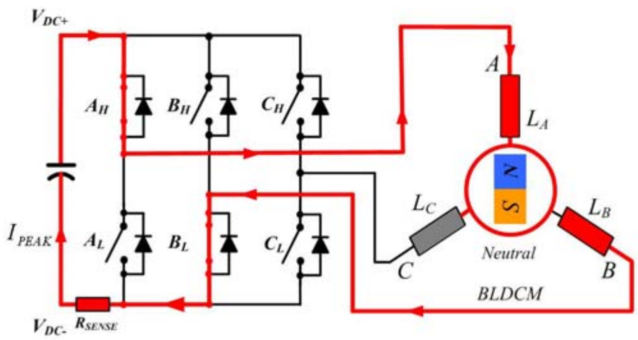
Number of poles	4
Rated power	897 [W]
DC bus voltage	310 [VDC]
Rated speed	4100 [r/min]
Rated current	6.1 [A]

A. Inductance Comparison Process

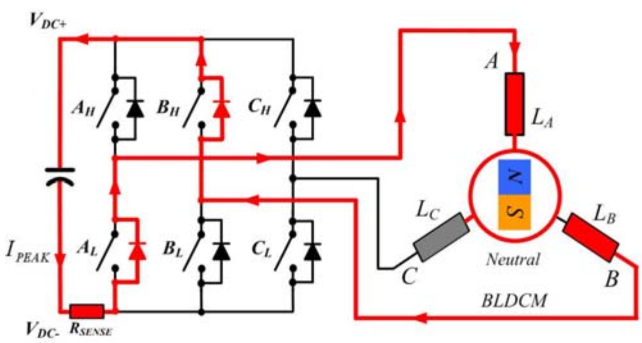
In this process, a sequence of two voltage pulses is injected to a pair of selected windings. As shown in Fig. 3, each voltage pulse injection consists of two intervals: the pulse-injecting interval and the free-wheeling interval. The operations of this process can be explained as follows.

1) First voltage pulse injection

The first voltage pulse is injected to the A- and B-windings by turning "*on*" switches A_H and B_L as shown in Fig. 3(a). During this pulse-injecting interval, phase A is connected to the positive dc bus, V_{DC+}, and phase B is connected to the negative dc bus, V_{DC-}, while phase C is floating without any current flow into it. Therefore, the voltage across the B-winding can be detected through the phase C terminal and the negative dc bus. Its equivalent circuit is simplified as depicted in Fig. 4(a).

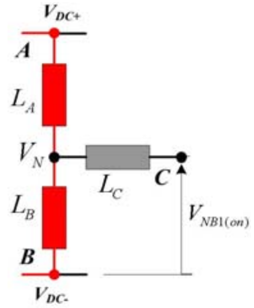


(a)

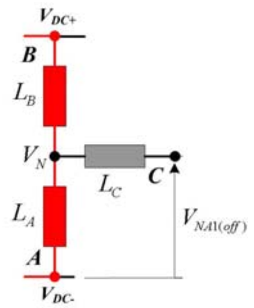


(b)

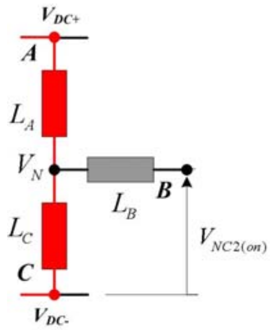
Fig. 3 Switching states for the BLDC drive in Fig. 1 during the first voltage-pulse injection. (a) pulse-injecting interval. (b) free-wheeling interval



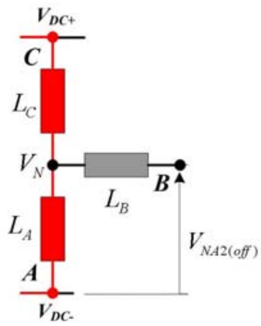
(a) pulse-injecting interval



(b) free-wheeling interval



(c) pulse-injecting interval



(d) free-wheeling interval

Fig. 4 Terminal voltage detection during the pulse-injecting and free-wheeling intervals of the first voltage-pulse injection as in (a)-(b), and of the second voltage-pulse injection as in (c)-(d).

Since the winding resistances and the current sensing resistor, R_{SENSE}, , are negligibly small, the dc bus voltage, V_{DC}, during the pulse-injecting interval can be approximated as

$$\begin{aligned} V_{DC} &\approx [L_A(\theta_0)+L_B(\theta_0)]\frac{di_{1(on)}}{dt} \\ &\approx L_A(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}}+L_B(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}}=V_{AN1(on)}+V_{NB1(on)} \end{aligned} \tag{1}$$

where L_A, L_B, and L_C are the A-, B- and C-phase winding inductances, θ_0 is the initial rotor position, $\Delta i_{1(on)}$ is the current change during this pulse-injecting interval, $T_{s1(on)}$ is the pulse-injecting interval time, and $V_{AN1(on)}$ and $V_{NB1(on)}$ are the voltage across the A- and B-windings during the first pulse-injecting interval respectively. From (1), the winding voltages, $V_{AN1(on)}$ and $V_{NB1(on)}$ can be rewritten in terms of V_{DC} as

$$V_{AN1(on)}=\frac{L_A}{L_A+L_B}\cdot V_{DC}\ ;\ V_{NB1(on)}=\frac{L_B}{L_A+L_B}\cdot V_{DC} \tag{2}$$

After the first pulse-injecting interval, the switches A_H and B_L are then turned off. Consequently, the corresponding free-wheeling interval occurs as illustrated in Fig. 3(b), and its equivalent circuit is shown in Fig. 4(b). The dc bus voltage during this free-wheeling interval can be approximated by

$$V_{DC} \approx -L_A(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}} - L_B(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}} = V_{NA1(off)} + V_{BN1(off)} \quad (3)$$

where $\Delta i_{1(off)}$ is the current change during this free-wheeling interval, $T_{s1(off)}$ is the free-wheeling interval time, and $V_{NA1(off)}$ and $V_{BN1(off)}$ are the voltage across the A- and B-windings during this free-wheeling interval respectively.

It should be noted that the total voltage drop across both A and B windings during the free-wheeling interval is opposite to that of the pulse-injecting interval, thus the immediate change of the bus voltage also reflects to A- and B-windings in the same manner. Therefore, it can be realized from (1) and (3)that

$$L_A(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}} = -L_A(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}}, \text{ or, } V_{AN1(on)} = V_{NA1(off)}$$

and

$$L_B(\theta_0)\frac{\Delta i_{1(on)}}{T_{s1(on)}} = -L_B(\theta_0)\frac{\Delta i_{1(off)}}{T_{s1(off)}}, \text{ or, } V_{NB1(on)} = V_{BN1(off)} \quad (4)$$

Also, the voltages across A- and B-windings during the free-wheeling interval, Fig. 4(b), are

$$V_{BN1(off)} = \frac{L_B}{L_A + L_B}\cdot V_{DC}\ ;\ V_{NA1(off)} = \frac{L_A}{L_A + L_B}\cdot V_{DC} \quad (5)$$

Finally, it can be re-expressed, from (2) and (5), that

$$V_{NA1(off)} - V_{NB1(on)} = \frac{(L_A - L_B)}{(L_A + L_B)}\cdot V_{DC} \quad (6)$$

From (6), it is obvious that the values of L_A and L_B can be compared to each other by voltage comparison between $V_{NA1(off)}$ and $V_{NB1(on)}$ which can be done simply since both of them are reference to V_{DC-}.

2) Second voltage pulse injection

With the same principle, the second voltage pulse with the same interval is injected to the A- and C- windings. Phase A winding is connected to V_{DC+} and phase B winding is connected to V_{DC-} by turning "*on*" switches A_H and C_L while phase B is floating. Then the switches A_H and C_L are turned off and, consequently, the corresponding free-wheeling interval occurs. Similar to the first pulse-injecting mentioned in the previous section, the equivalent circuit during the second pulse-injecting interval and the corresponding free-wheeling interval are shown in Fig. 4(c) and (d). Therefore, the detected voltages across A- and C-windings, and hence L_A and L_C, can be compared to each other according to the following equation:

$$V_{NA2(off)} - V_{NC2(on)} = \frac{(L_A - L_C)}{(L_A + L_C)}\cdot V_{DC} \quad (7)$$

where $V_{NC2(on)}$ is the voltage across the C winding during the second pulse-injecting interval and $V_{NA2(off)}$ is the voltage across the A winding during the second free-wheeling interval. These voltages can be simply measured through the phase B terminal with reference to V_{DC-}.

Additionally, the relative values of L_B compared to L_C can be determined from the detected phase voltage $V_{NB1(on)}$ and $V_{NC2(on)}$ as

$$V_{NB1(on)} - V_{NC2(on)} = (L_B - L_C)\cdot\frac{L_A}{(L_A + L_B)(L_A + L_C)}\cdot V_{DC} \quad (8)$$

Finally, it can be summarized that the winding inductance values, L_A, L_B, and L_C, can be compared to each other by using (6) - (8). The relationship between the inductance comparisons and possible initial rotor positions (the north pole) can be determined as listed in Table 2.

However, a single inductance comparison can map into two opposite sectors as is evident in Fig. 5. For example, the condition, $L_B > L_C > L_A$, can be identified the possible initial position in either 0 - 30° or 180 - 210° sectors. Thus, to determine which one of the two opposite sectors the rotor magnet pole actually locates, an additional process is required. This extra process is called "polarity determination" as described next.

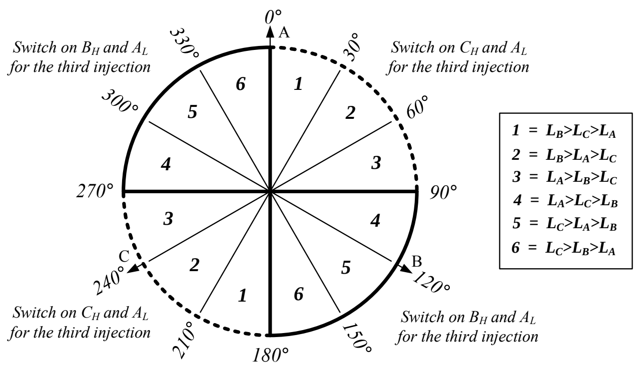


Fig. 5 Determination of the initial rotor position based on the inductance comparison along with the switch assignment for the third injection.

B. Polarity Determination Process

For the purpose of rotor magnet polarity detection, it is required to apply the *third pulse-voltage injection*. It should be noted that the peak dc-link currents (I_1, I_2, and I_3) are sampled and then recorded at the ends of all three pulse-injecting intervals. The subscripts (*1, 2,* and *3*) denote the order of injection. The determination of the magnet polarity can be explained in the following paragraph.

The north and south poles of the rotor magnet can be determined from the idea that the winding currents from the injected pulse voltages can further increase or decrease the stator saturation, and then can slightly decrease or increase the inductance respectively, as a function of the magnet polarity which was clearly stated in [1] and is also shown in Fig. 2. With this idea, the sector where the north pole locates can be discriminated. Therefore, once the two opposite sectors are already identified, the third voltage pulse which apparently causes the stator to further increase or decrease the saturation level will be applied. Due to this restriction, the third pulse voltage injection is chosen according to the following conditions:

$$\begin{aligned}
&\text{If } 0^\circ < \theta_0 < 90^\circ \text{ or } 180^\circ < \theta_0 < 270^\circ \\
&\text{then switch on } C_H \text{ and } A_L \text{ for the 3rd injection} \\
&\text{and compare } I_2 \text{ with } I_3. \\
&\text{Else if } 90^\circ < \theta_0 < 180^\circ \text{ or } 270^\circ < \theta_0 < 360^\circ \\
&\text{then switch on } B_H \text{ and } A_L \text{ for the 3rd injection} \\
&\text{and compare } I_1 \text{ with } I_3.
\end{aligned}$$

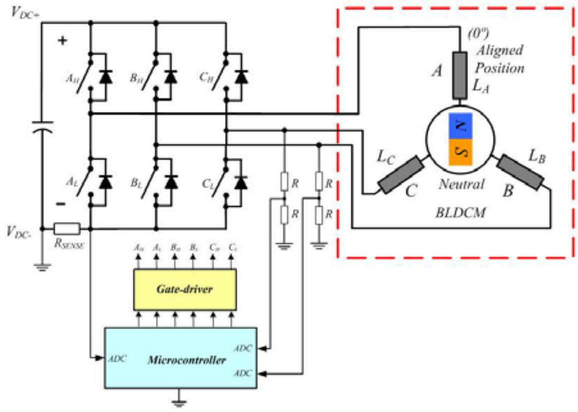
These conditions are also specified in Table 2 and Fig. 5. Finally, the determination of the rotor position using the proposed method can be summarized in Table 2.

Table 2 Determination of initial rotor position

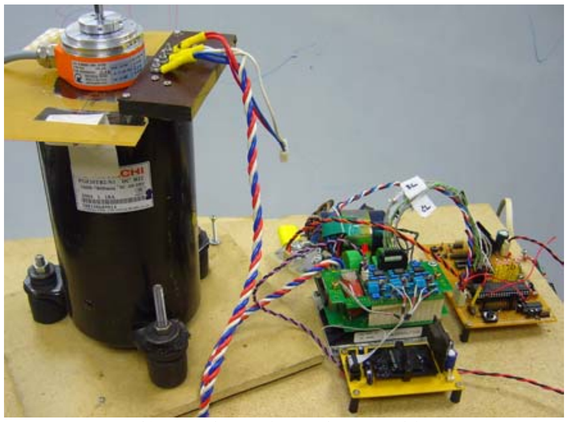
Phase Voltage Comparison	Inductance Comparison	Possible Initial Position	3rd Injection	Peak Current	Initial Rotor Position
$V_{NB1}>V_{NA1}$ $V_{NC2}>V_{NA2}$ $V_{NB1}>V_{NC2}$	$L_B>L_C>L_A$	0°< θ$_0$<30°	C_H, A_L	$I_2>I_3$	0°<θ$_0$<30°
		180°< θ$_0$<210°		$I_3>I_2$	180°< θ$_0$<210°
$V_{NB1}>V_{NA1}$ $V_{NC2}<V_{NA2}$ $V_{NB1}>V_{NC2}$	$L_B>L_A>L_C$	30°< θ$_0$<60°	C_H, A_L	$I_2>I_3$	30°< θ$_0$<60°
		210°< θ$_0$<240°		$I_3>I_2$	210°< θ$_0$<240°
$V_{NB1}<V_{NA1}$ $V_{NC2}<V_{NA2}$ $V_{NB1}>V_{NC2}$	$L_A>L_B>L_C$	60°< θ$_0$<90°	C_H, A_L	$I_2>I_3$	60°< θ$_0$< 90°
		240°< θ$_0$<270°		$I_3>I_2$	240°< θ$_0$<270°
$V_{NB1}<V_{NA1}$ $V_{NC2}<V_{NA2}$ $V_{NB1}<V_{NC2}$	$L_A>L_C>L_B$	90°< θ$_0$<120°	B_H, A_L	$I_3>I_1$	90°< θ$_0$<120°
		270°< θ$_0$<300°		$I_1>I_3$	270°< θ$_0$<300°
$V_{NB1}<V_{NA1}$ $V_{NC2}>V_{NA2}$ $V_{NB1}<V_{NC2}$	$L_C>L_A>L_B$	120°< θ$_0$<150°	B_H, A_L	$I_3>I_1$	120°< θ$_0$<150°
		300°< θ$_0$<330°		$I_1>I_3$	300°<θ$_0$< 330°
$V_{NB1}>V_{NA1}$ $V_{NC2}>V_{NA2}$ $V_{NB1}<V_{NC2}$	$L_C>L_B>L_A$	150°< θ$_0$<180°	B_H, A_L	$I_3>I_1$	150°< θ$_0$<180°
		330°< θ$_0$<360°		$I_1>I_3$	330°< θ$_0$<360°

III. Experimental Results

The experimental system which was set up to validate the proposed method is shown in Fig. 6 . It can be seen that only four additional resistors has been included into a typical drive system. The pulse-injecting time applied in this experiment was 150 μs by using dsPIC30F4011 (16-bit microcontroller), with a 310 volts dc bus voltage. The BLDC machine is star-connected, 4 poles type. Its parameters are summarized in Table 1Table 1.



(a) Sensorless BLDC drive system configuration



(b) Actual experimental BLDC drive

Fig. 6 Sensorless BLDC drive system.

To avoid adverse effects during transient state due to parasitic parameters and non-idealities in the test system, the phase voltage response with reference to the negative dc bus, are sampled and recorded at the middle of the pulse-injecting interval (75µs after the beginning of the voltage injection) and around the middle of free-wheeling interval (75µs after the end of the voltage injection). The peak currents are also sampled and recorded at the ends of three pulse-injecting intervals (150µs after the beginning of each voltage injection).

Fig. 7 shows the corresponding voltages and currents resulting from the injections at the actual position θ_0 = 43°. From the figure, it can be seen that the conditions of phase voltage comparisons are $V_{NB1}>V_{NA1}$, $V_{NC2}<V_{NA2}$ and $V_{NB1}>V_{NC2}$. Consequently, the choice of the third pulse injection is switching on C_H and A_L and also the comparison between I_2 and I_3. According to Table 2, the estimate rotor position is in 30º<θ$_0$<60º sector.

Figs 8(a) and (b) show the phase voltages and DC-link currents resulting from the injections at θ_0 = 125° and 305° respectively. It is indicated from the figures the voltage comparisons of the both rotor positions are the same, *i.e.*, $V_{NB1}<V_{NA1}$, $V_{NC2}>V_{NA2}$ and $V_{NB1}<V_{NC2}$, and then their possible estimate position is in the sector 120º<θ_0<150º or 300º<θ_0<330º. However, the results of their current comparison between I_1 and I_3 show that the estimate initial position of the former is in the sector 120º<θ_0<150º, and the latter 300º<θ_0<330º. This is to show that by using the proposed method, the polarity of the rotor magnet, and hence rotor position, can be clearly determined with 30º resolution.

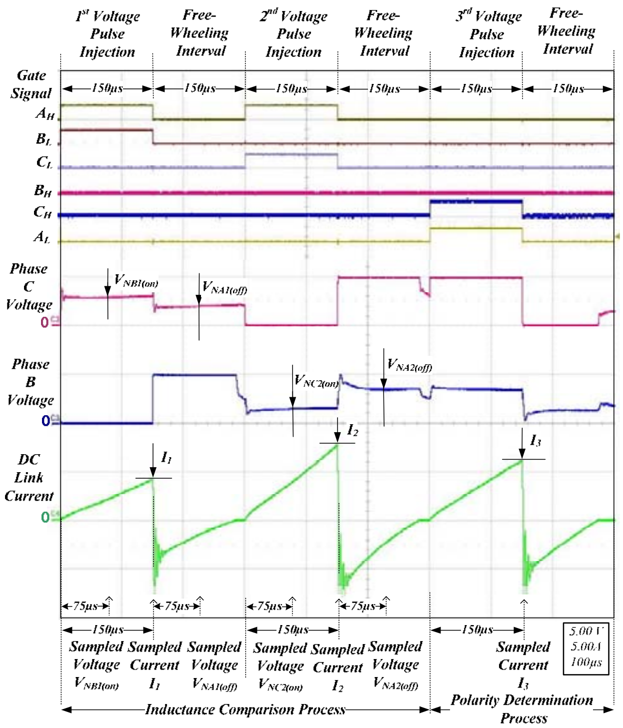
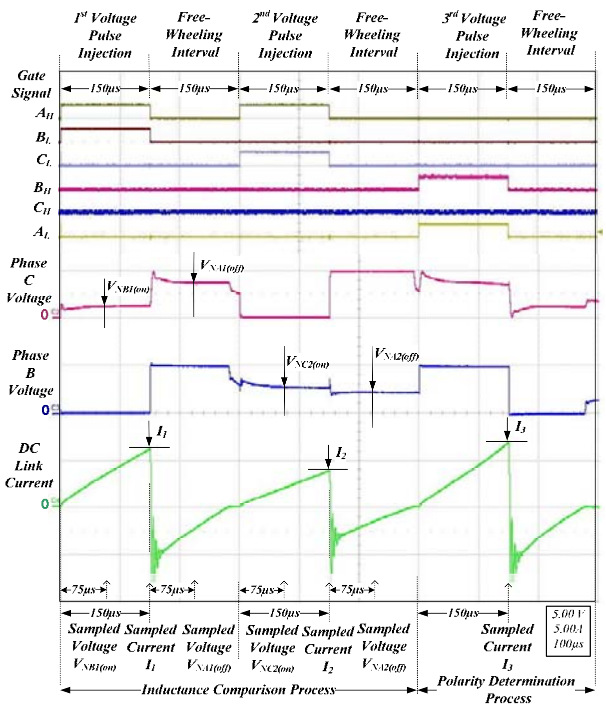
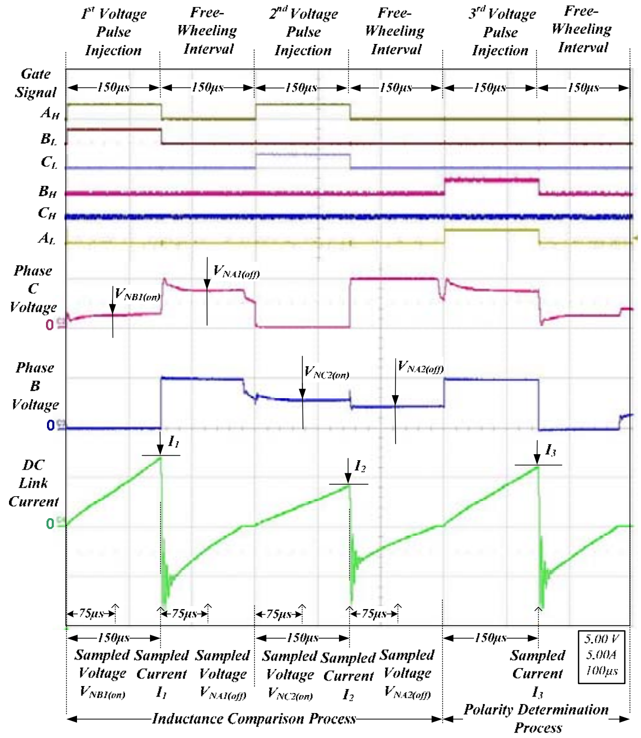


Fig. 7 Actual phase voltages and DC link current of both process (43°)



(a)



(b)

Fig. 8 Actual phase voltages and DC link current of both process (a) – (125°) (b)- (305°) The neutral voltages and DC link current

IV. CONCLUSION

A simple initial rotor position estimation method at standstill is introduced in this paper. It is based on the stator inductance variation due to influences of saturation of the stator iron, and the flux due to the position of the rotor magnets. In the proposed method, only three narrow voltage pulses are applied to the phase windings to determine the rotor position and 30 degree resolution is achieved. Additionally only one sensing resistor is added into a typical BLDC drive. It is particularly suitable for sensorless BLDC drive applications in which low cost is the major requirement. Moreover, no machine parameters are required.

V. REFERENCES

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as outstanding paper presented at the International Conference on Electrical Machines and Systems 2007.

December 12, 2007

Yong Joo Kim

Dr. Yong Joo Kim

General Chairman of ICEMS2007

ICEMS 2007

ICEMS2007, October 8-11, 2007, Olympic Parktel, Seoul, Korea

Dear Mr. P. Champa

We would like to thank you sincerely for your contribution to ICEMS2007 (International Conference on Electrical Machines and Systems 2007) which was held on October 8-11, 2007 in Seoul, Korea. Without your active participation, the conference was never finished successfully. Giving you our cheers, the organizing committee also would like to deliver our warmest acknowledgement to you.

We hope the conference had given you a beneficial experience exchanging various aspects of the relevant industries and discovering new opportunities in the still growing technical fields for you and other participants as well. In addition, it is expected that you had a memorable time with your colleagues.

Further, we are very proud to announce that the first issue "Journal of ICEMS (tentative name)' will be published on September 2008 to meet the request of potential participants in the future. Providing the critically invaluable contribution to our society, I am sure that it will be the one of outstanding journals. Regarding this, it would be much appreciated if you would contribute your updated paper(s) (awarded as outstanding papers of ICEMS2007) again to the Journal of ICEMS. For your convenience, we would let you have more detailed information and remind you of the paper submission process around March 2008.

We certainly look forward to seeing you in near future, thank you again for coming ICEMS2007. We all wish you have good health and fortune with your family.

Sincerely yours, with my kind regards

Dr. Yong Joo Kim
General Chairman of ICEMS2007